Synopsis

Ph. D. in Physics

Nuclear Structure and Two-proton, One-proton Decay Studies of Light, Medium, Heavy and Superheavy Nuclei

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SYNOPSIS

Nucleus is the central core of an atom. All nuclei that exist in nature are not stable. The nucleus with the magic number of protons or neutrons are stable against decay. The nuclei show a sudden and discontinuous behavior at the particular number of protons and neutrons and their behavior seems to be magic and hence those proton number and neutron number are called as *magic numbers*. For radioactive unstable nuclei, their nuclear force is no longer able to hold the nucleons inside the nucleus and it decays by the emission of radiation either in the form of rays or particles and is termed as *radioactivity*. The unstable nucleus reaches stable state by the emission of particles like alpha, beta and gamma rays and these decays are classified under basic radioactivity. With advent in the experimental techniques and the identification of new isotopes beyond the limit of stability, paved the way for the observation of exotic type of decays such as one-proton (1p) emission, two-proton (2p) emission, neutron emission and cluster decay, in this extreme mass region.

The nuclei lying beyond the limit of stability, are unstable and the boundary limit at which the addition of a nucleon becomes unbound, along the proton and neutron axes are called proton dripline and neutron dripline respectively. One-proton and two-proton radioactivity are exotic phenomena, in which one-proton and two-protons are emitted from the neutron deficient proton-rich nuclei respectively. They were theoretically predicted first in 1960 [1, 2] and it was observed experimentally in later years. The nuclei which are lying away from the magic nuclei are found to deviate from the spherical shape. The deformed nuclei are found to have two different shapes (i.e., prolate and oblate deformations). The studies on both theoretical and experimental, carried out thus far, resulted in more information about the nuclear structure and nuclear properties which played a significant role in the growth of this field. This thesis deals with two aspects. One is on the study on nuclear energy levels, where the single particle energies of protons and neutrons are computed using binding energies and emergence of new magic numbers. Second aspect is on exotic nuclear decays such as two-proton radioactivity and one-proton radioactivity of drip line nuclei.

The thesis consists of eight chapters, organized in the following manner: Chapter 1 deals with the description about the basic and exotic decay modes and nuclear models which deals with the occurrence of magic numbers and also the evolution of superheavy nuclei. The objectives and the organization of the thesis are presented at the end of this chapter. Reviews on both experimental and theoretical works on the occurrence of traditional magic numbers and also the evolution of new magic numbers for the nuclei lying in the dripline region are

discussed in Chapter 2. Reviews on two-proton and one-proton emitters, identified using different experimental techniques are also discussed. Two-proton and one-proton radioactivity dealt using various theoretical approaches are discussed in Chapter 2.

Chapter 3 explains the methodology of the work. Various methods have been carried out to calculate the single particles energies for both protons and neutrons in order to show the occurrence of traditional magic numbers as well as the emergence of new magic numbers beyond the limit of stability. Temperature independent Yukawa-plus-exponential macroscopic mass formula [3] is used to calculate binding energies of the chosen nuclei. Using binding energies, the single particle energies of both protons and neutrons are computed. With the use of single particle energies, spin-orbit splitting of protons and neutrons are calculated. Unified nuclear potential developed by Krappe *et al* [4] is the generalization of the modified liquid drop model by taking a double volume integral of the Yukawa folding function and also with the incorporation of parameter which accounts for the surface diffuseness and short-range nuclear interactions. This model is used to analyse spontaneous emission of fragments heavier than alpha particle and used to study alpha and cluster decay. The overlapping region is approximated using third order polynomial by Nix [5]. Shanmugam and Kamalakaran [6] have used the third- order polynomial for the case of overlapping potential and Coulomb-plus-Yukawa-plus-exponential model (YEM) for the portion of non-overlapping potential, to study the competition between the alpha and cluster decay for the spherical configuration and deformed configuration [7]. Coulomb-plus-Yukawa-plus-exponential modelfor spherical configuration with the incorporation of deformations in both parent and daughter nuclei keeping the emitted nucleus spherical are described in Chapter 3, which is used to study 2p and 1p radioactivity.

Magic number plays a significant role in the development of the field of nuclear physics. Research is going on to identify the new isotopes in the exotic mass region. Identification of new magic numbers in the dripline region is necessary to support is aspect. This is the key factor behind work of Chapter 4. Temperature independent Yukawa-plus-exponential macroscopic formula is used to calculate the binding energy of the nucleus. In order to arrive at the experimental binding energies, volume energy coefficient and surface energy coefficient are used as fitting parameters. The volume energy and surface energy coefficients are varied up to a limit of ± 1 MeV from their values a_v = 16 MeV and a_s = 21.13 MeV. Then, the core and core ± nucleon nuclei are chosen to compute the single particle energies of both protons and neutrons. Here, the core represents the magic nuclei which is

either singly magic or doubly magic and core ± nucleon nuclei represent its adjacent nuclei which are having, either a particle or hole in it. The single particle energies of both protons and neutrons are determined using the binding energies of the core and core ± nucleon nuclei. Single particle energies are calculated to confirm the occurrence of traditional magic numbers and the study has been extended to confirm the emergence of new magic numbers in both light mass and superheavy mass region. In case of light mass region, the nuclei lying along the dripline with the mass number ranging from A = 30 to 36 are chosen for the study and gap in energy levels corresponding to N, Z = 14 and 16, confirms the occurrence of new magic numbers, where the new magic number Z = 14 has been identified from the study of the heaviest stable isotope ^{42}Si [8, 9]. Whereas for the superheavy mass region, gap in single particle energy levels at Z = 92 and 114 and N = 164 and 184 shows the occurrence of new magic numbers. Thus far, in this mass region, the emergence of new magic numbers has not yet been identified experimentally. However, it is confirmed in many articles. Initial work is presented in proceedings [10]. The occurrence of new magic number at Z = 92 is reported in the present work [11] and in Ref. [12]. Spin-orbit splitting of both protons and neutrons are calculated. The reduced spin-orbit splitting is found to proportional to $A^{-2/3}$ and it decreases with increase in the mass number. Results pertaining to the above are discussed in Chapter 4.

Chapter 5 describes about the analysis of two-proton radioactivity using Coulomb-plus-Yukawa-plus-exponential model. Experimentally identified two-proton emitters are taken for the analysis and their half-lives are calculated. In the present study, the total penetrability is the product of penetrability over the non-overlapping region and spectroscopic factor which accounts for the preformation probability. In order to arrive at the experimental half-lives, the parameter χ in the spectroscopic factor is used as a fitting parameter and it is varied between the limit 0.0001 to 1. Using the best fitted spectroscopic values, an analysis is done with the macroscopic quantities such as mass number A and atomic number Z. From the analysis, a cubic polynomial relation between spectroscopic factor and macroscopic numbers A and Z is arrived. The half-lives are calculated for the experimentally identified two-proton emitters using the fitted relation and it is found to have a good match with the experimental values. The study is extended to find whether the experimentally identified two-proton emitters are true 2p emitters. Their Q-values (Q_{1p}) are calculated for one-proton emission and it is found, that out of eight cases, three cases are said to have negative Q_{1p} values and remaining five cases are having positive Q_{1p} values. The branching ratio is calculated for both 2p and 1p emission in order to determine the preferred decay mode. The study has been extended to predict 2p

emitters in the light and medium mass region. Further, determination of the preferred decay mode of the 2p emitters is studied. Their Q_{1p} and half-lives are computed using fitted relation and the branching ratio is calculated between 2p and 1p emission. In order to show the 2p emission is similar to other binary decay process, analysis have been done to determine the relation between the logarithmic reduced width and physical parameters such as fragmentation potential and pairing gap. The results pertaining to the above study are discussed in this chapter [13, 14].

Chapter 6 is the extension of the previous chapter which deals with the study two-proton emission using Coulomb-plus-Yukawa-plus-exponential model with the incorporation of deformation. Half-lives are calculated for the experimentally identified deformed two-proton emitters. Here, the total penetrability is the product of penetrability over the non-overlapping region and the spectroscopic factor which accounts for the preformation probability. The fitted relation obtained for the spectroscopic factor through the study of spherical 2p emitter using YEM is used here. Among eight experimentally identified 2p emitters, three cases are having deformed daughter nucleus, whereas remaining cases are having spherical shaped daughter nuclei. The half-lives calculated with the incorporation of deformation is found to have good match with the experimental half-lives. Further, the study has been extended to predict the deformed 2p emitters and their half-lives are calculated. For the prolate configuration, the area under the potential is found to be low, therefore the penetration probability increases which in turn reduces the half-lives. Whereas for the oblate case, the area under the potential is high, therefore the penetration probability decreases which in turn reduces the half-lives. Due to the limited availability of the experimental cases, the predicted cases are taken for the analysis of whether the two-proton emission is similar to other binary decay process and the results pertaining to this study are presented in this chapter.

One-proton radioactivity for both spherical and deformed configuration are studied using Cubic-plus-Coulomb-plus-Yukawa-plus-exponential model and discussed in Chapter 7. The half-lives are calculated for 40 experimentally identified 1p emitters for both spherical and deformed configuration. It is established, that there exists a competition between one-proton emission and alpha decay. Q_{α}-values and their half-lives are calculated and the branching ratio is calculated between 1p emission and alpha decay of the proton emitters in order to determine the preferred decay mode. The branching ratio calculated for both spherical and deformed configuration matches well with the branching ratio calculated using experimental values. The study has been extended to analyze the half-lives of predicted 1p emitters for both

configurations. Totally 33 deformed 1p emitters are taken for analysis. Among 33 cases, 21 cases are found to have prolate deformed daughter nucleus and remaining 12 cases are having oblate shaper daughter nucleus. It is found that for the prolate shaped daughter nucleus, the half-life is found to be reduced whereas for the oblate cases, the half-life is found to be increased. Further, the study is extended to predict 1p emitters in the superheavy mass region. The competition between the 1p emission and alpha decay are analyzed and it is found that for the medium mass region, one-proton emission is the preferred decay mode whereas in the superheavy mass region, alpha decay is the dominant decay mode. The results related to this analysis are discussed in detail in this chapter.

The summary of the present work is given in Chapter 8 and the significance and conclusion drawn from the occurrence of traditional magic numbers and evolution of new magic numbers in both light and superheavy mass region are discussed. Summary and conclusion drawn from the study of two-proton emission and one-proton emission of both spherical and deformed configuration are explicitly presented along with the future scope for the extension of the work.

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